Jet properties from di-hadron correlations in p+p collisions at $\sqrt{s}$ =200 GeV

Jan Rak PHENIX collaboration
Jyvaskyla University & HIP, Finland

Everything you want to know about jet-physics can be found using a 2-particle correlations, OK, almost everything…

- Analysis of PHENIX high p_T π^0 trigger associated charged hadron distributions in p+p data at $\sqrt{s}$=200 GeV.

  $\rightarrow$ 1 . 10^8 gamma3 triggered events (2x2 EMcal>1GeV/c) analyzed.

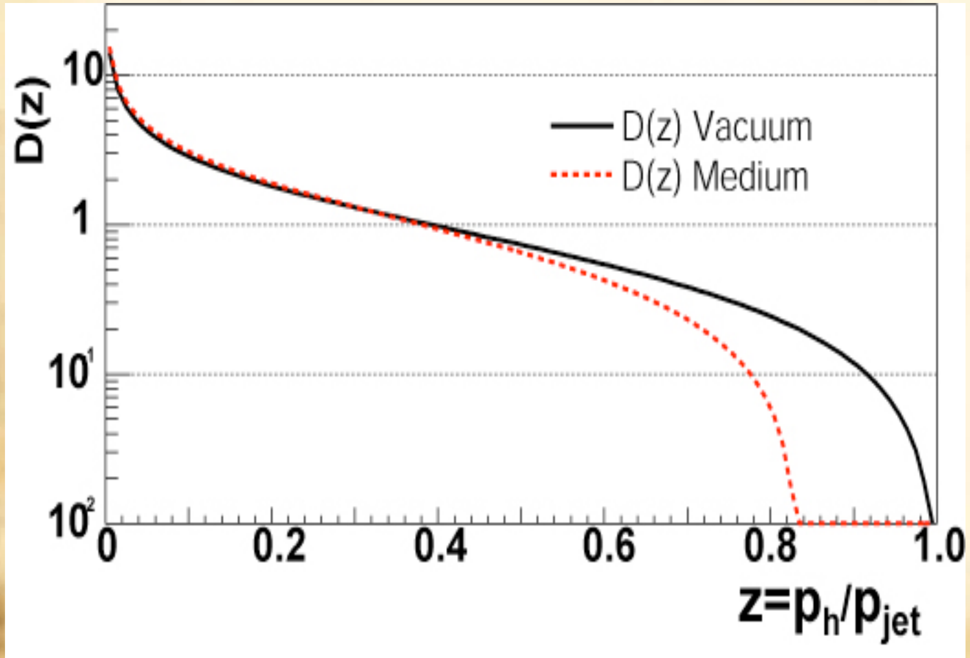
- Jet kinematics from 2-particle correlation
- Trigger biases in 2-particle correlation - words of caution.
- Lorentz invariant 2D k_T smearing.
- (In)Sensitivity of trigger associated distributions to the shape of the fragmentation function *D(z)*.
- Results on $\langle k^2_T \rangle$ evolution with trigger $p_{Tt.}$

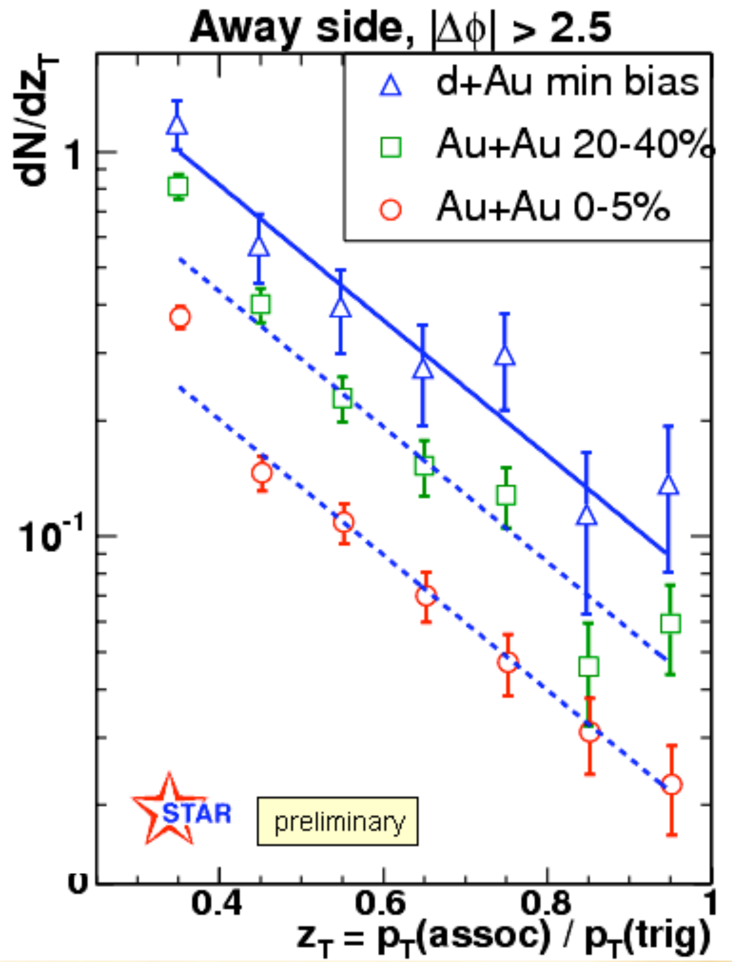
Modification of the fragmentation fcn

pQCD nature of jet quenching should be accompanied by modification of partonic properties
e.g. softening of the fragmentation function

Gyulassy, Vitev, Wang and Zhang

nucl-th/0302077





Away side yield is suppressed in central collisions
But the amount of suppression is independent of pT,assoc

Jet quenching at RHIC - do we see *Induced Gluon Radiation* ?

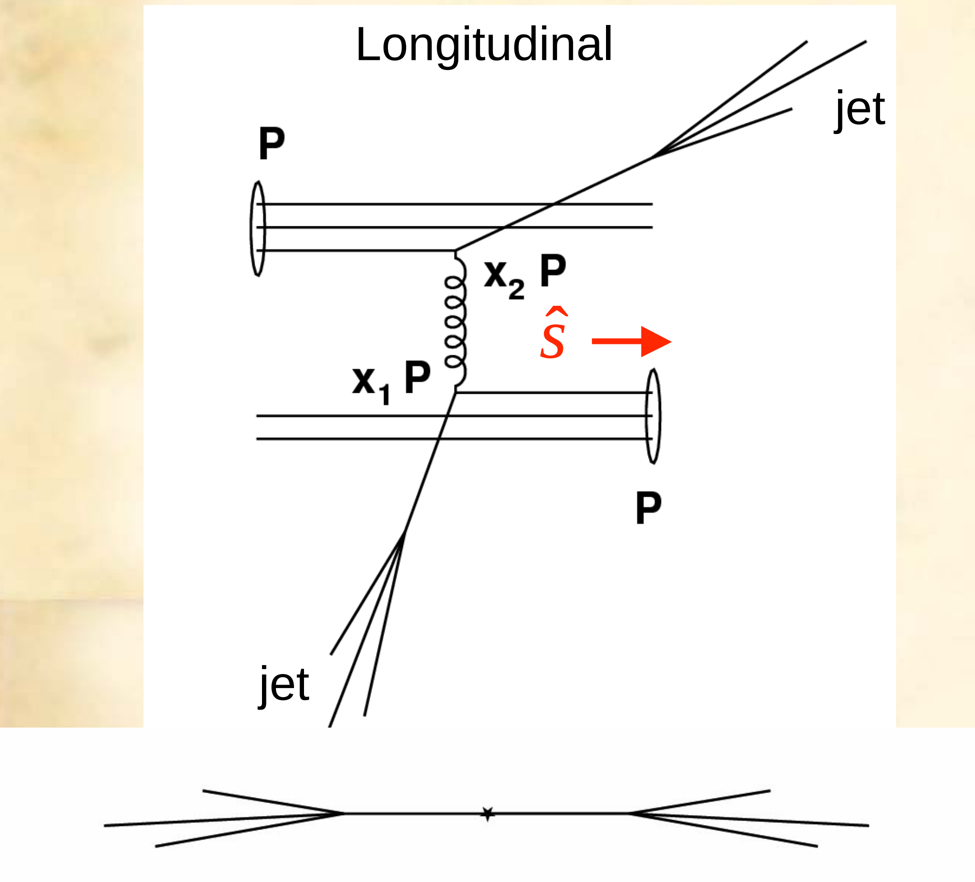
Maybe but why there is

- Similar suppression pattern of high-p_T electrons from semi-leptonic *D* and *B* mesons decays; PRL 91, 172302 (2003). Where is the 'dead cone' ? Is there unique dN_g/dy for light/heavy quarks quenching?
- No broadening of the associated correlation peak (nucl-ex/051000). According Ivan Vitev (Phys. Lett. **B630**, 78 (2005)) there should be a significant broadening.
- induced gluon radiation should strongly violate the x_T scaling in contrast to what is seen in the data - see *Brodsky, Pirner and Raufeisen*, hep-ph/0510315

Detailed understanding of unmodified parton properties

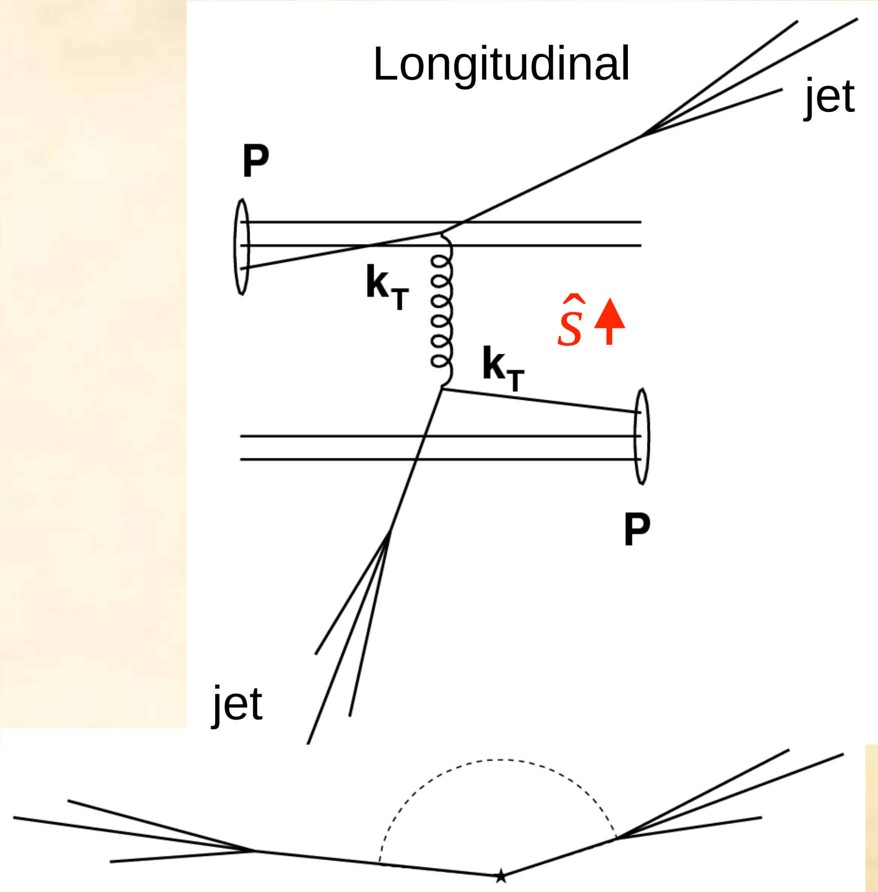
CRUTIAL

Hard scattering – k_T



transverse

- acoplanar in $P_L \times P_T$ space
- collinear in $P_X \times P_Y$ space

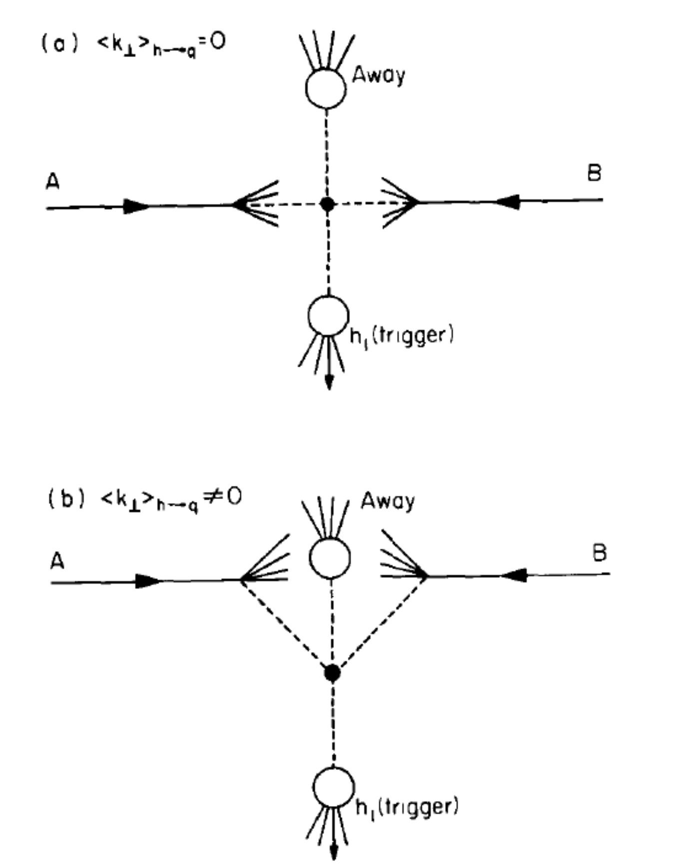


transverse

- acoplanar in $P_L \times P_T$ space
- acoplanar in $P_X \times P_Y$ space

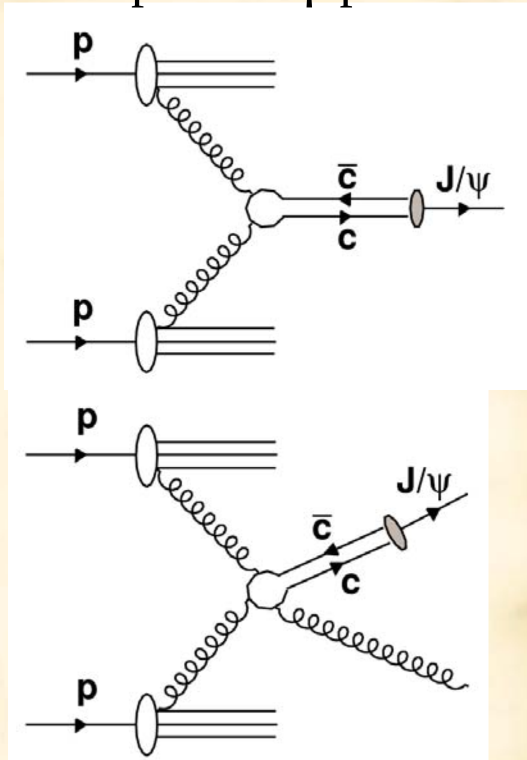
Origin of k_T

Intrinsic k_T "fermi motion"



Soft QCD NLO radiation.

As an example - J/ψ production.



Power law tail @ large value of $p_{T,pair}$

$\langle p_T \rangle_{J/\psi}$ =1.8±0.23±0.16 GeV/c

Phys. Rev. Lett. 92, 051802, (2004).

$$\langle k_T^2 \rangle = \frac{\langle p_{T,pair}^2 \rangle}{2} = \langle k_T^2 \rangle_{\text{intrinsic}} + \langle k_T^2 \rangle_{\text{NLO}} + \langle k_T^2 \rangle_{\text{soft}}$$

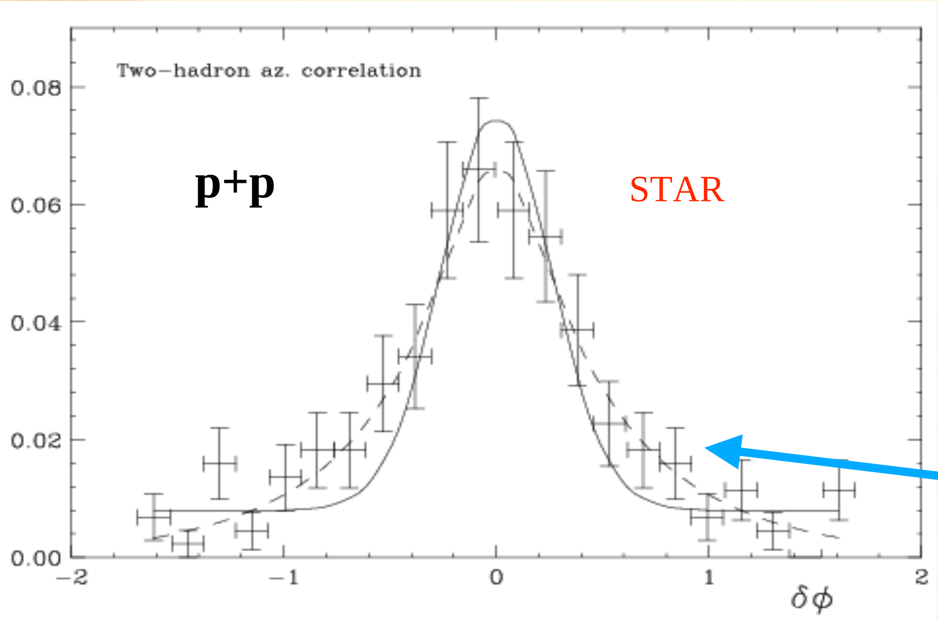
Gussian @ $p_{T,pair} \to 0$

Leading-Log resummation

Vogelsang,Sterman,Keusza

Nucl Phys A721,591(2003)

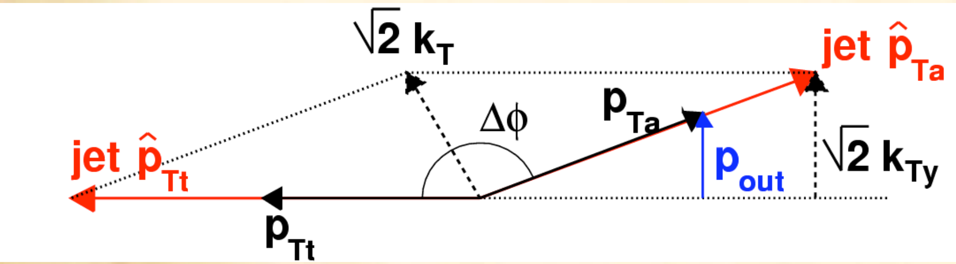
Soft Gaussian + hard power law

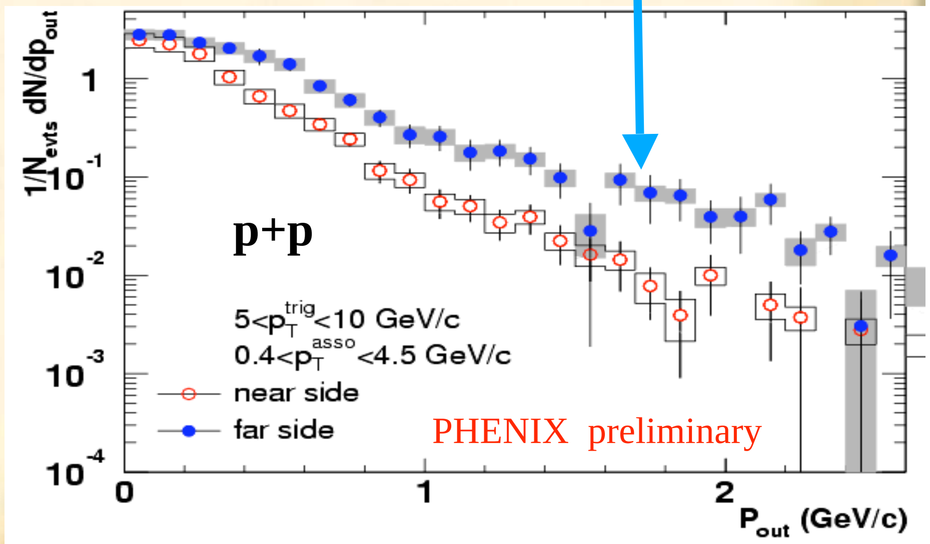


D. Boer and W. Vogelsang,
Phys. Rev. D69 (2004) 094025

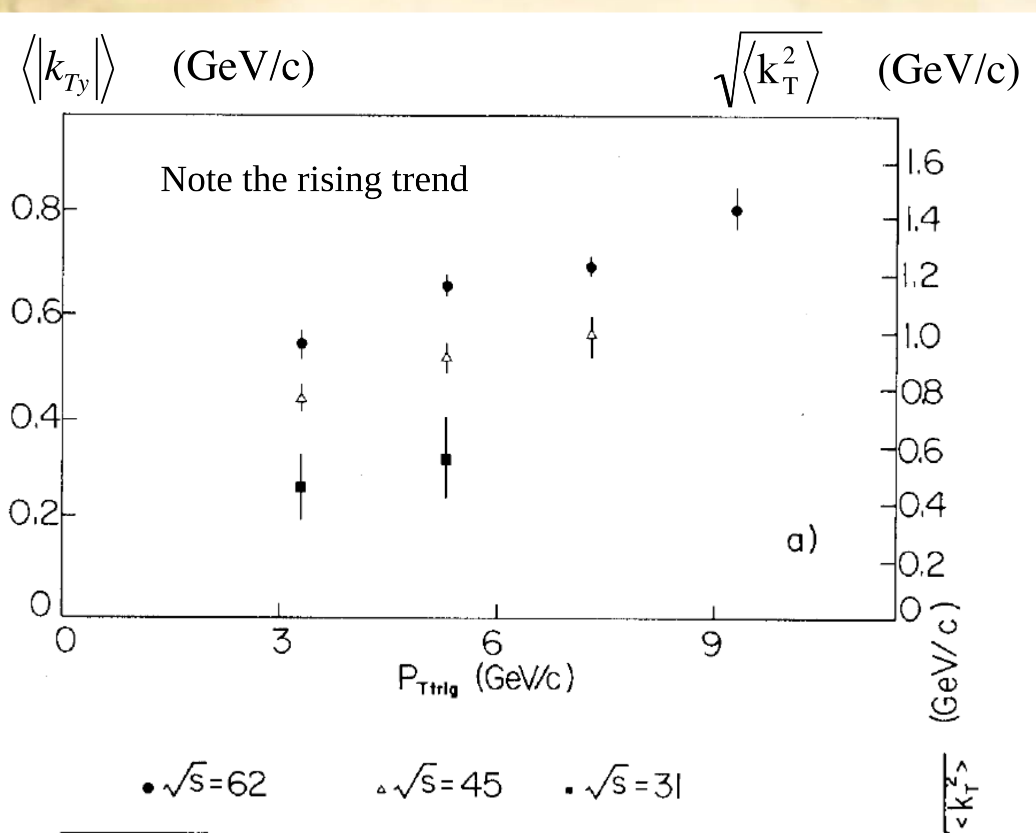
J. Qiu and I. Vitev,
Phys. Lett. B570 (2003) 161

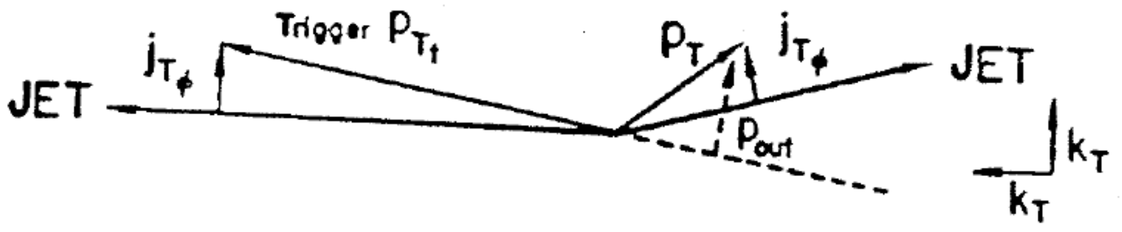
radiative tails





ISR CCOR - √s = 30-60 GeV





$$\boxed{\langle |p_{\rm out}| \rangle^2 = \langle |j_{Ty}| \rangle^2 + x_E^2 (\langle |j_{Ty}| \rangle^2 + 2 \langle |k_{Ty}| \rangle^2)}$$

A.L.S. Angelis, …
M.J. Tannenbaum
Phys Lett 97B (1980)

k_T is a 2D vector hence

$$\sqrt{\langle k_T^2 \rangle} = \frac{2}{\sqrt{\pi}} \langle k_T \rangle = \sqrt{\pi} \langle |k_{Ty}| \rangle$$

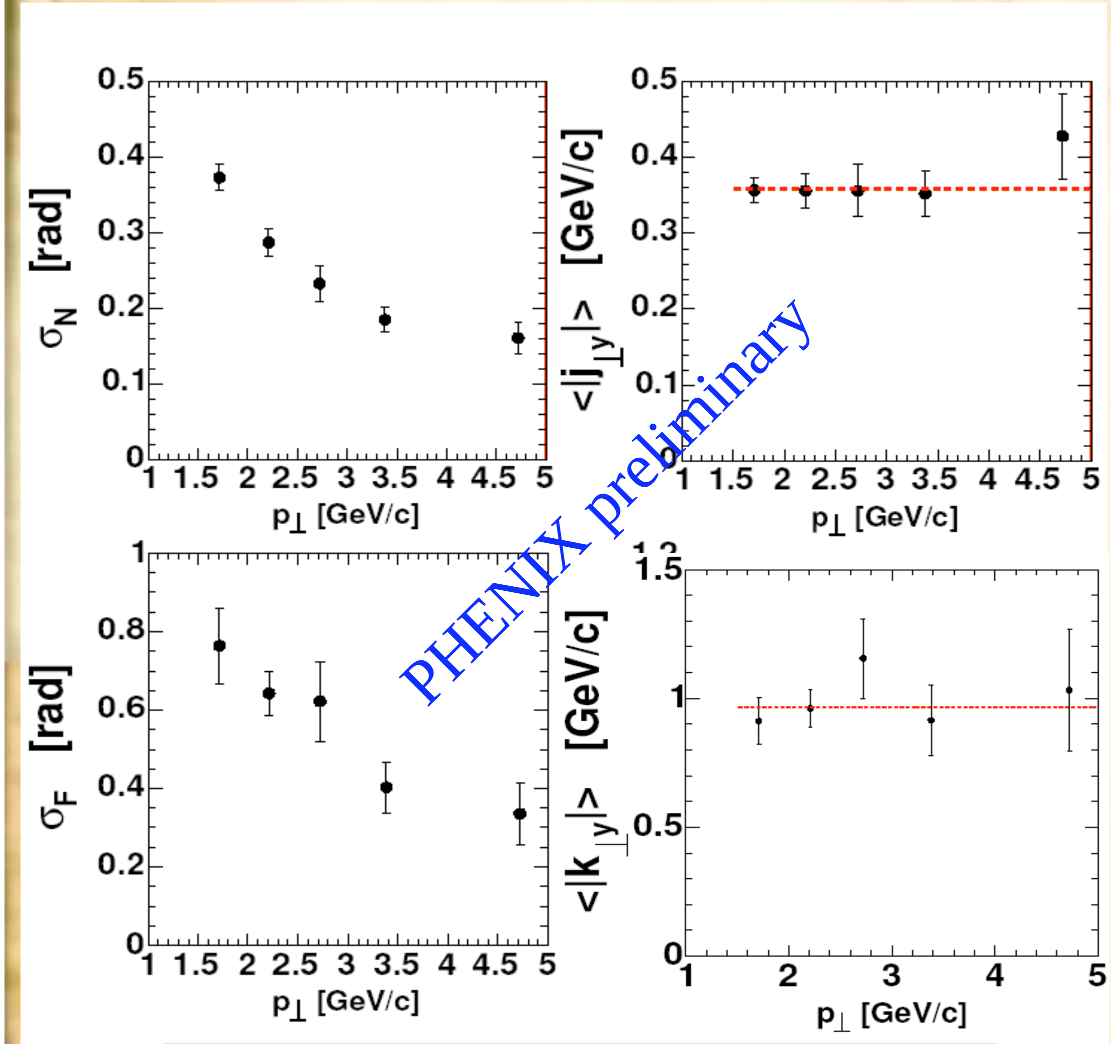
$\langle k^2_T \rangle$ causes acoplanarity

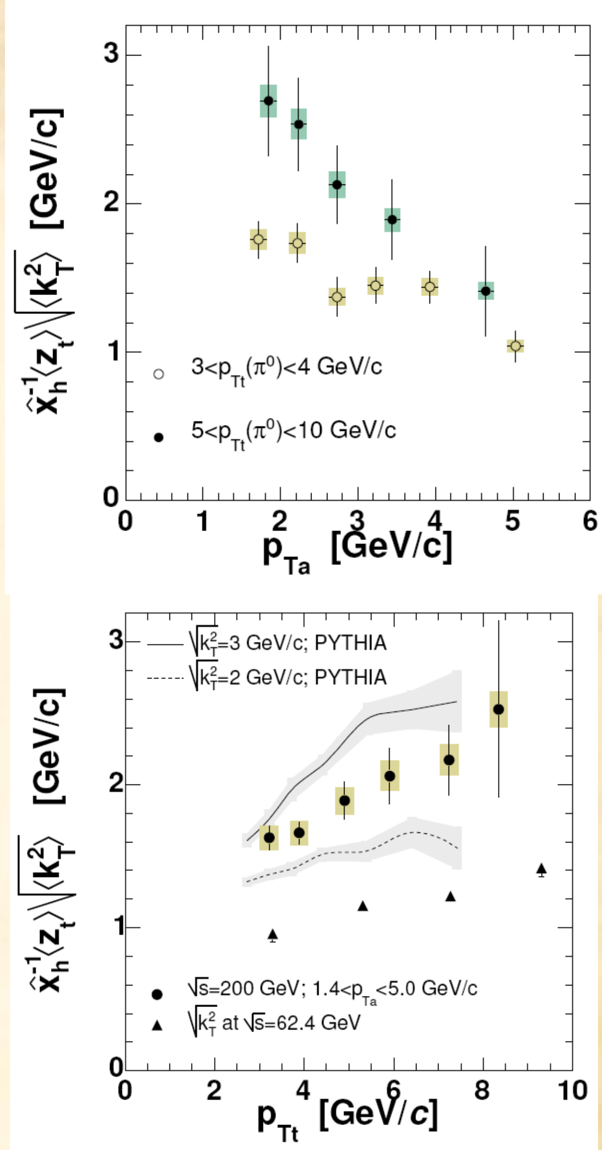
$\langle p^2_{out} \rangle$ transverse momentum component of the away-side particle measures accoplanarity

Feynman Field Fox Tannenbaum assumed 'hadron-parton duality' (z=1) and x_E is a two particle equivalent of z.

Looks as a simple analysis, right?

Is it really that easy ?





Shown at QM04 - fixed correlations $p_{Ttrigger}=p_{Tassoc}$

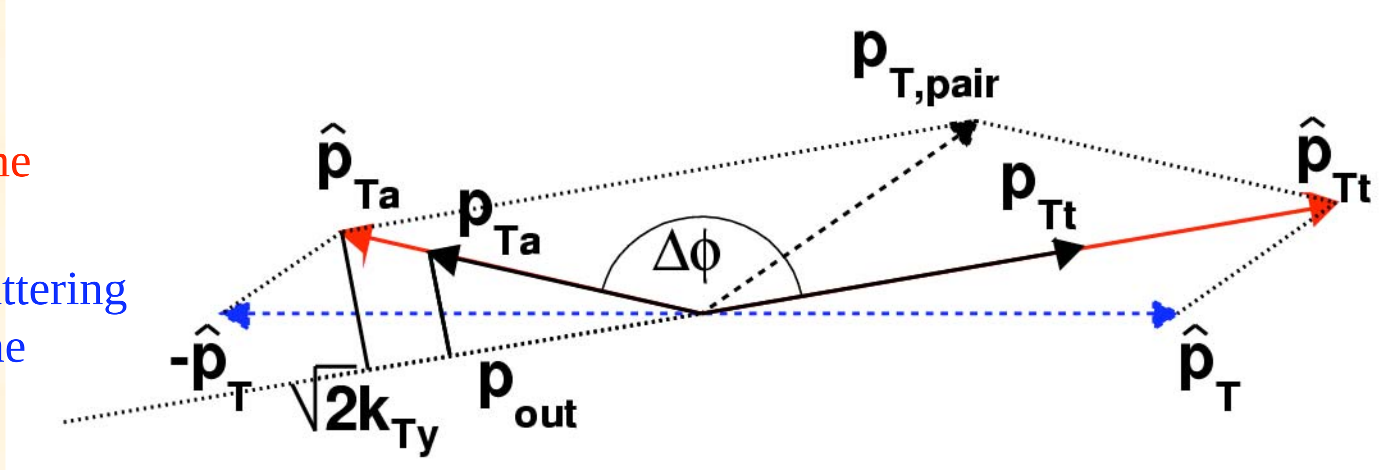
The real fun starts when $p_{Ttrigger}\neq p_{Tassoc}$

Lesson I. “k_T acoplanarity”

$p_{T,pair}$ Lorentz boost preserves $M^2_{inv} = 4\hat{p}_T^2 = 2\hat{p}_{Tt}\hat{p}_{Ta} - 2\vec{\hat{p}}_{Tt}\vec{\hat{p}}_{Ta}$

Lab frame

Hard scattering rest frame



$$\langle|p_{out}|\rangle = \sqrt{2}\langle|k_{Ty}|\rangle \frac{p_{Ta}}{\langle\hat{p}_{Ta}\rangle} \quad \Rightarrow \quad \sqrt{\langle p_{out}^2\rangle} = \langle z_t\rangle \sqrt{\langle k_T^2\rangle}\,\frac{x_h}{\hat{x}_h}$$

Jet momenta imbalance due to k_T smearing

$$\hat{x}_h = \frac{\langle\hat{p}_{Ta}\rangle}{\langle\hat{p}_{Tt}\rangle} \qquad x_h = \frac{p_{Ta}}{p_{Tt}}$$

partonic

$$\boxed{\hat{x}_h^{-1}\langle z_t\rangle\sqrt{\langle k_T^2\rangle} = x_h^{-1}\sqrt{\langle p_{out}^2\rangle - \langle j_{Ty}^2\rangle(1+x_h^2)}}$$

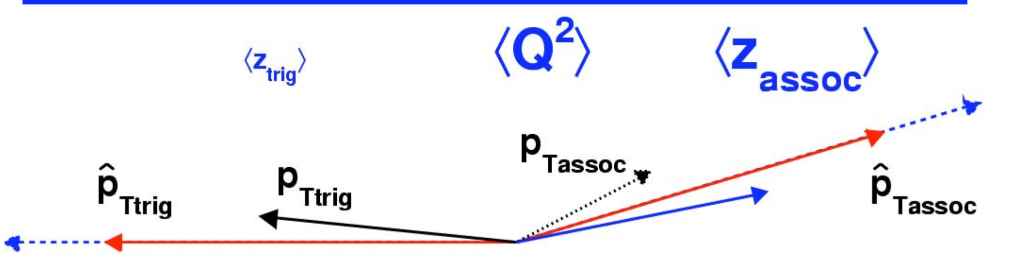
hadronic

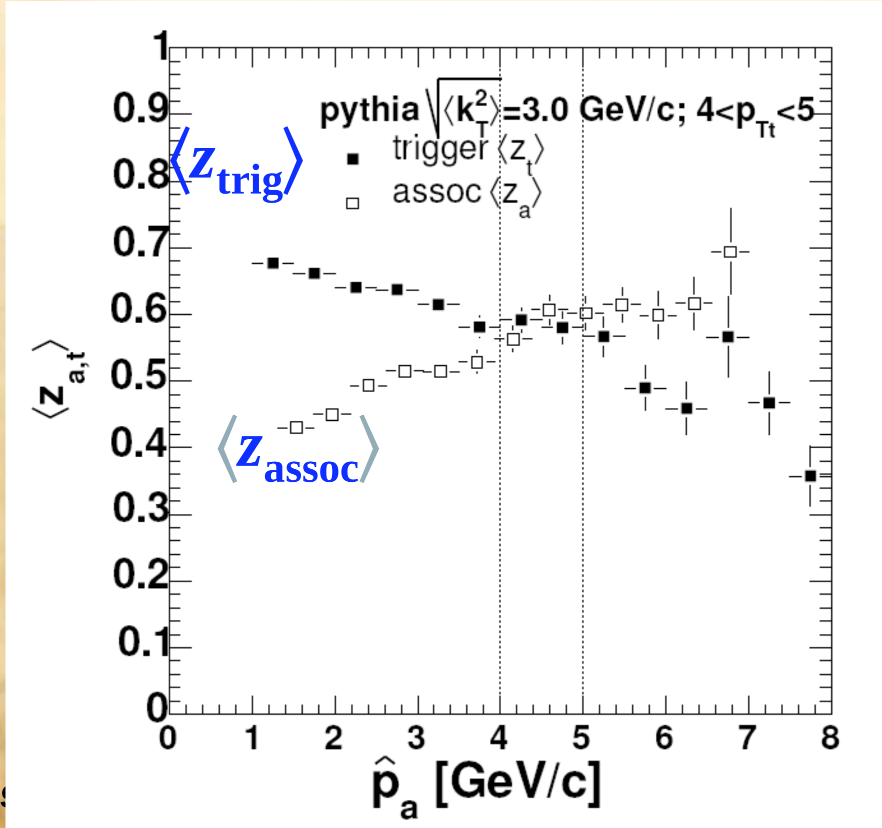
$$\langle|p_{\rm out}|\rangle^2 = \langle|j_{Ty}|\rangle^2 + x_E^2(\langle|j_{Ty}|\rangle^2 + 2\langle|k_{Ty}|\rangle^2) \qquad x_E = \frac{p_{Ta}}{p_{Tt}}\cos\Delta\varphi$$

Lesson II

There are ALWAYS two types of trigger biases when correlating $p_{Ttrigger} \neq p_{Tassoc}$

z-bias; steeply falling/rising D(z) & PDF(1/z)

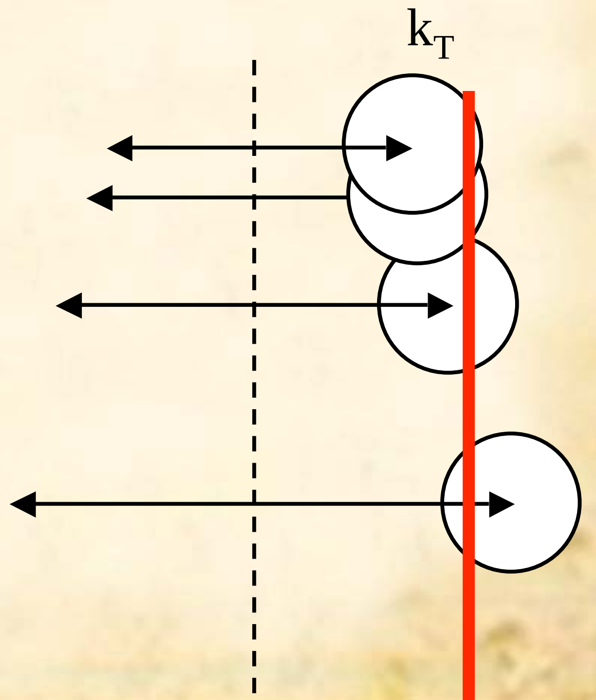




hat-x_h bias

Selecting events with $p_{Tt} > p_{Ta}$ forces k_T vector toward trigger jet:

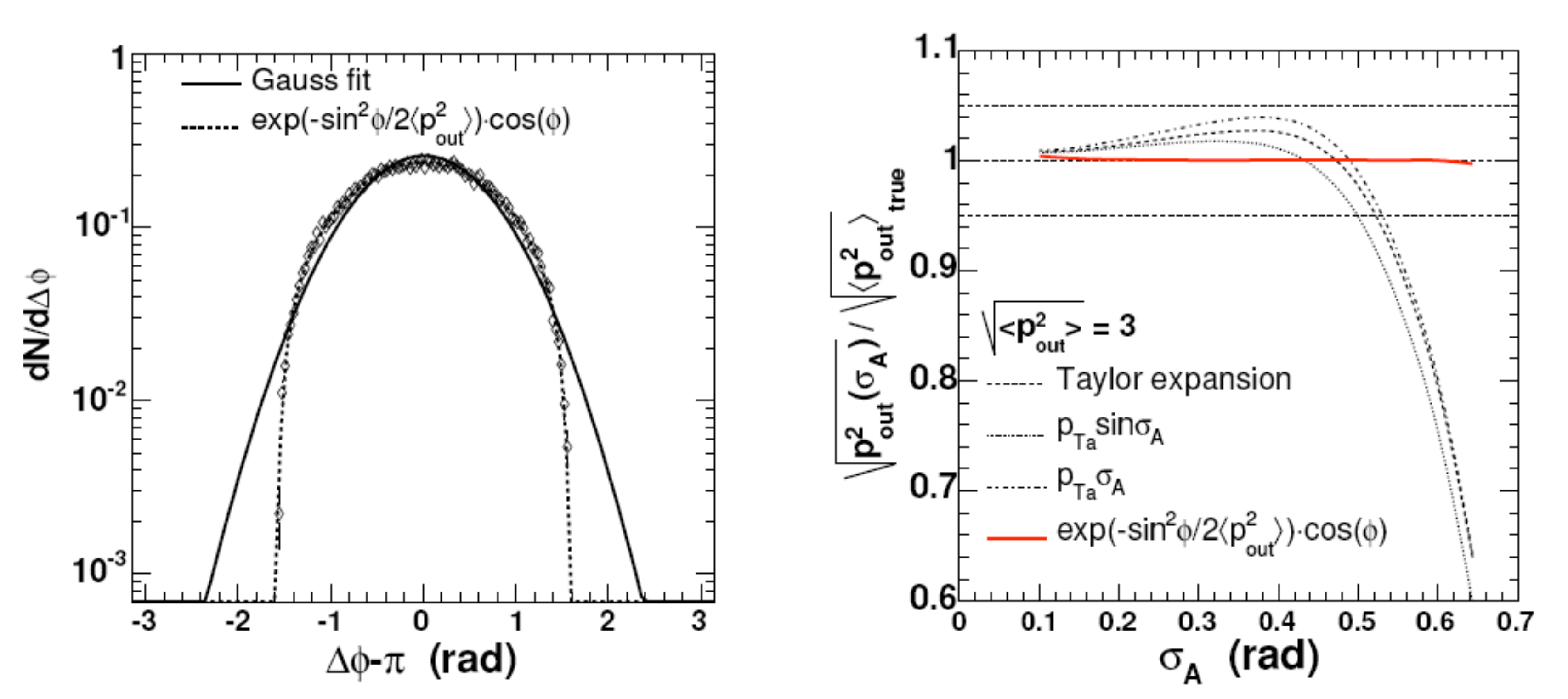
$$\left\langle \hat{p}_{Ttrigg} \right\rangle > \left\langle \hat{p}_{Tassoc} \right\rangle$$



Away side Δφ peak is not a Gaussian !

Lesson III

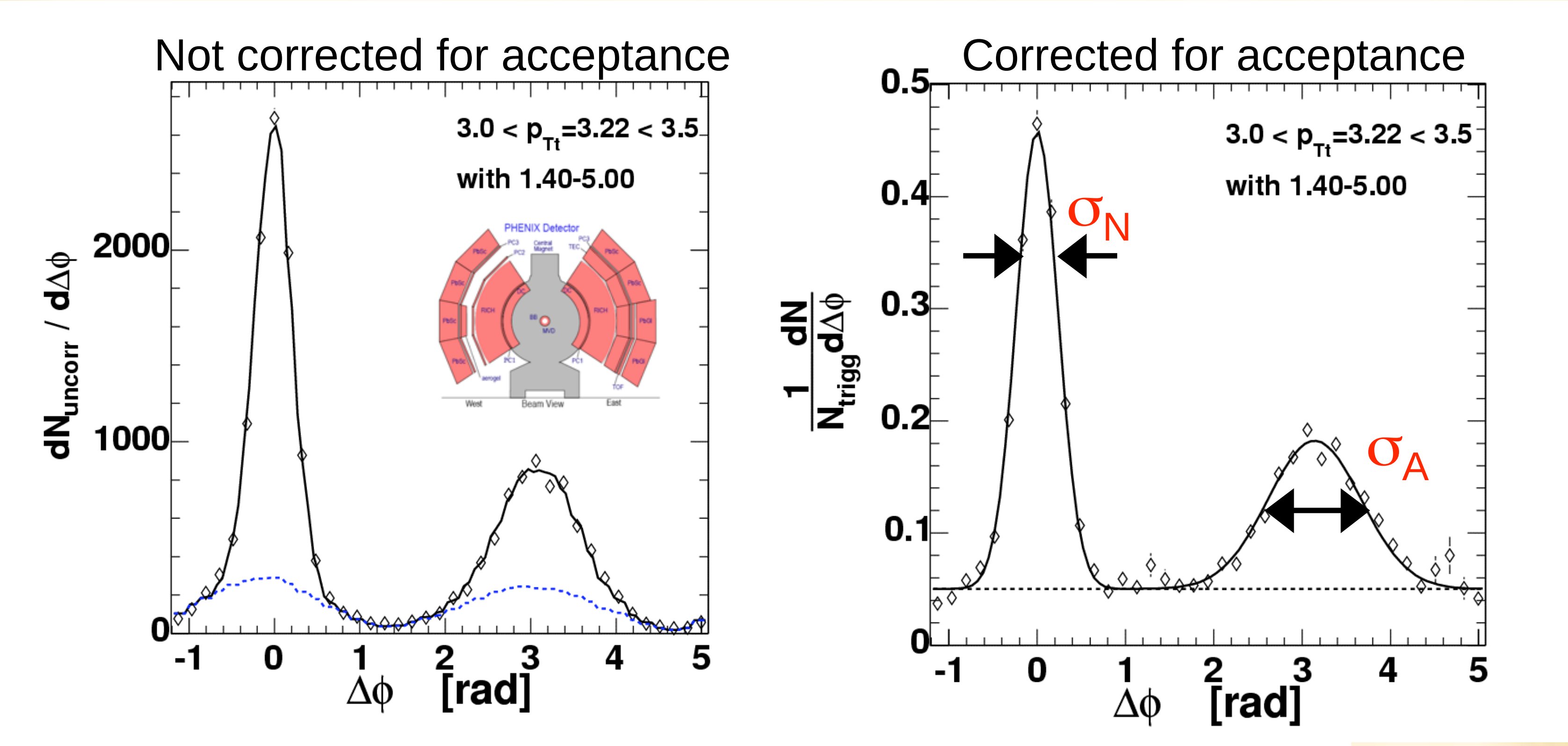
It caused some confusion. Exctraction of $\langle p_{out} \rangle$ from angular width of the away side peak - see e.g. P. Levai *et.all* hep-ph/0502238 does not converge.



$$\frac{dN_{away}}{d\Delta\phi}\bigg|_{\pi/2}^{3\pi/2} = \frac{dN}{dp_{\rm out}}\frac{dp_{\rm out}}{d\Delta\phi} = \frac{-p_{T{\rm a}}\cos\Delta\phi}{\sqrt{2\pi\left\langle p_{\rm out}^2\right\rangle}{\rm Erf}\left(\frac{\sqrt{2}p_{T{\rm a}}}{\sqrt{\left\langle p_{\rm out}^2\right\rangle}}\right)}\exp\left(-\frac{p_{T{\rm a}}^2\sin^2\Delta\phi}{2\left\langle p_{\rm out}^2\right\rangle}\right)$$

This distribution was fitted to the away-side peak; $\langle p_{out} \rangle$ = free parameter.

π^o - $h^\pm$ correlation functions p+p $\sqrt{s}$=200 GeV

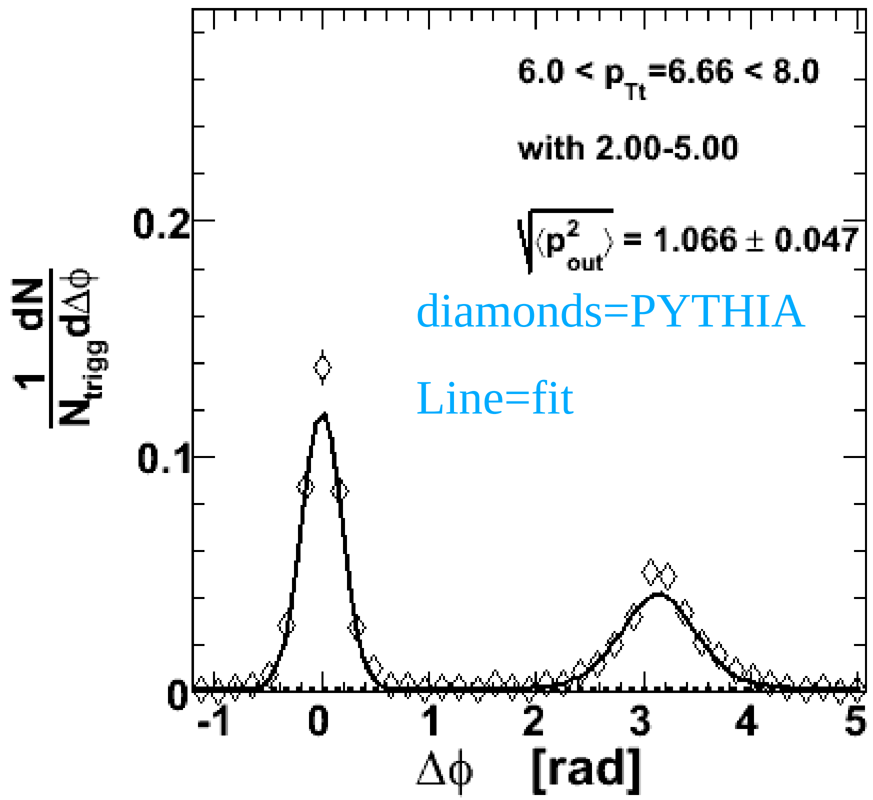


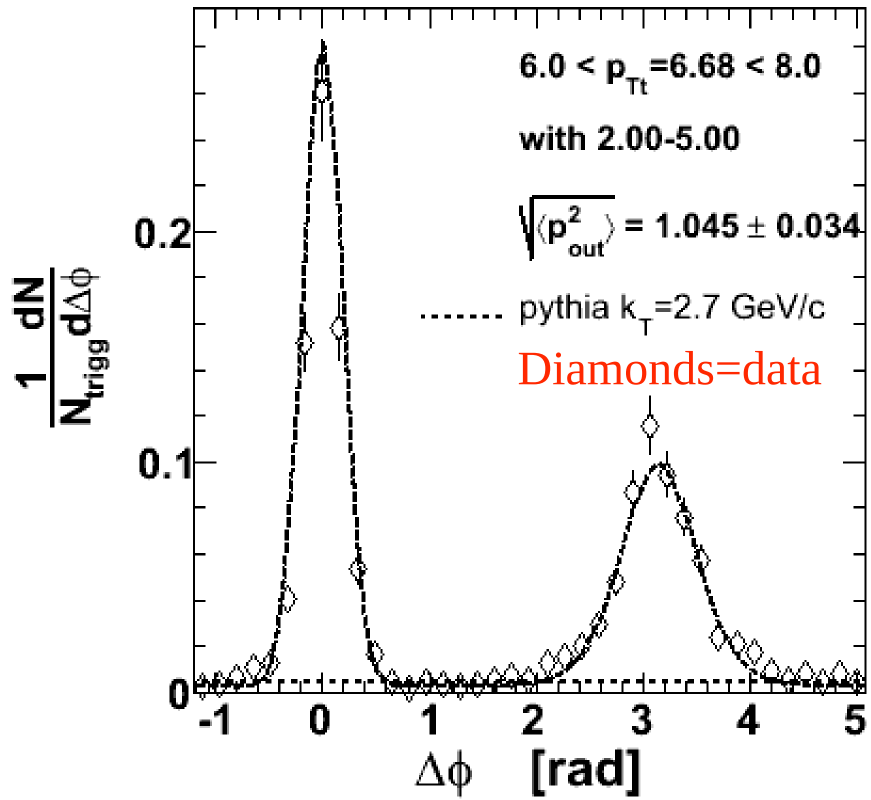
$\sigma_N \propto \langle j_T \rangle$ jet fragmentation transverse momentum

$\sigma_F \propto \langle k_T \rangle$ parton transverse momentum

$Y_A \propto$ folding of D(z) and final state PDF.

Data to PYTHIA comparison

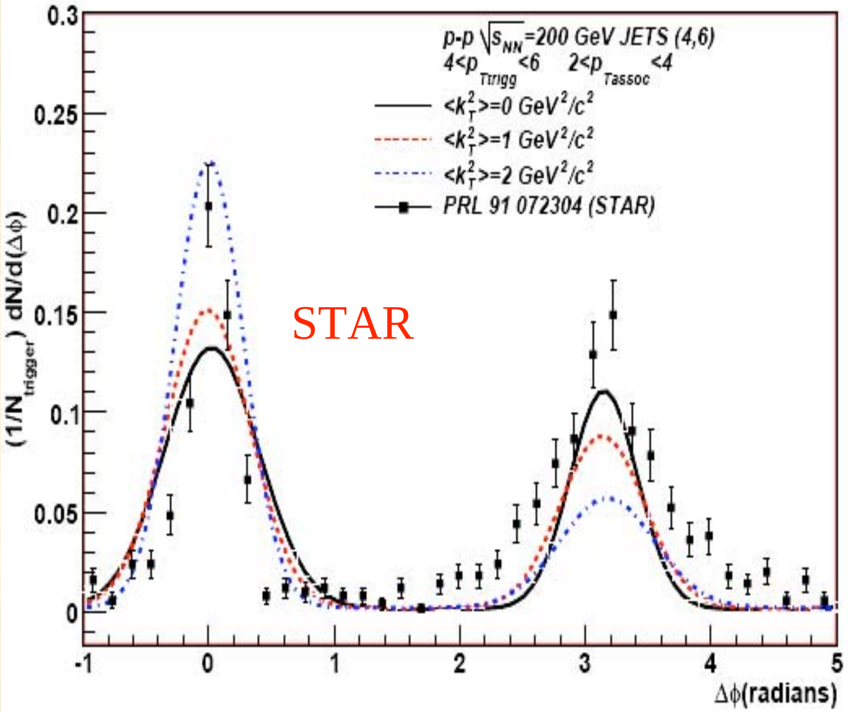


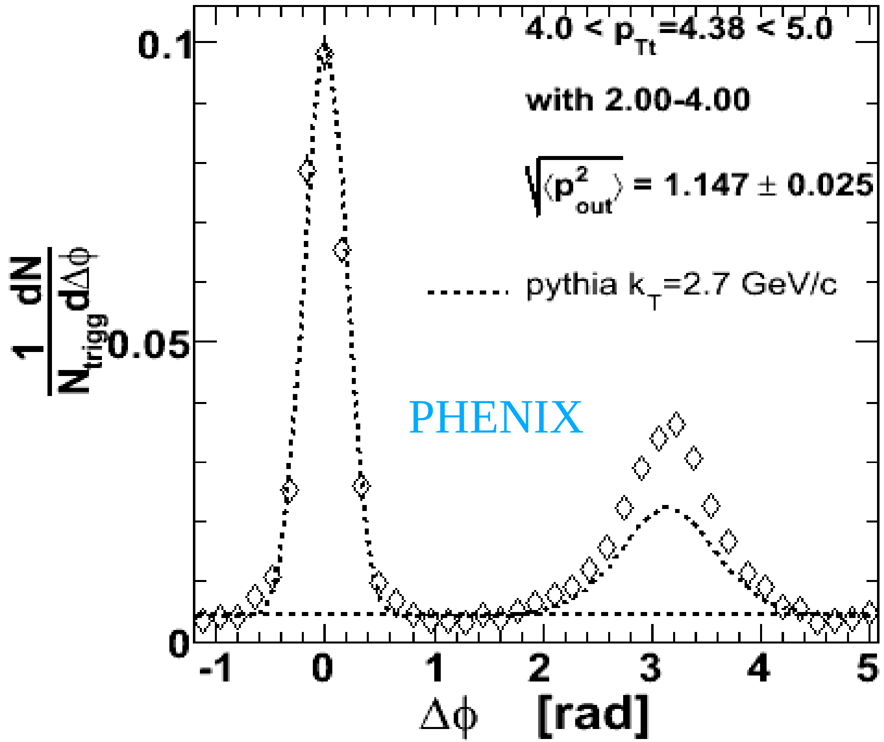


There is a factor of 2 less yield in PYTHIA (might be a trivial factor), however, the width and relative yields of away/near side are in good agreement.

STAR $2<p_{Ta}<4<p_{Tt}<6$ GeV/c

hep-ph/0604257





GURE 2. Azimuthal distributions for p+p collisions at $\sqrt{s_{NN}}$ = 200 GeV, experimental data [6] nulations with different $< k_T^2 >$

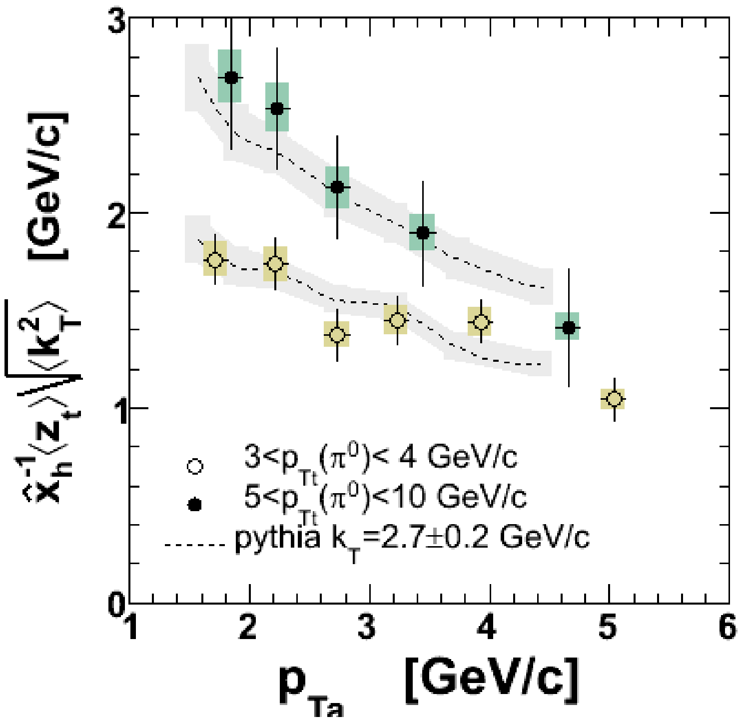
$$g(k_{T1},k_{T2}) = \frac{1}{2\pi\sigma_1^2}exp(-\frac{k_{T1}^2}{2\sigma_1^2}) + \frac{1}{2\pi\sigma_2^2}exp(-\frac{k_{T2}^2}{2\sigma_2^2}) \quad (4)$$

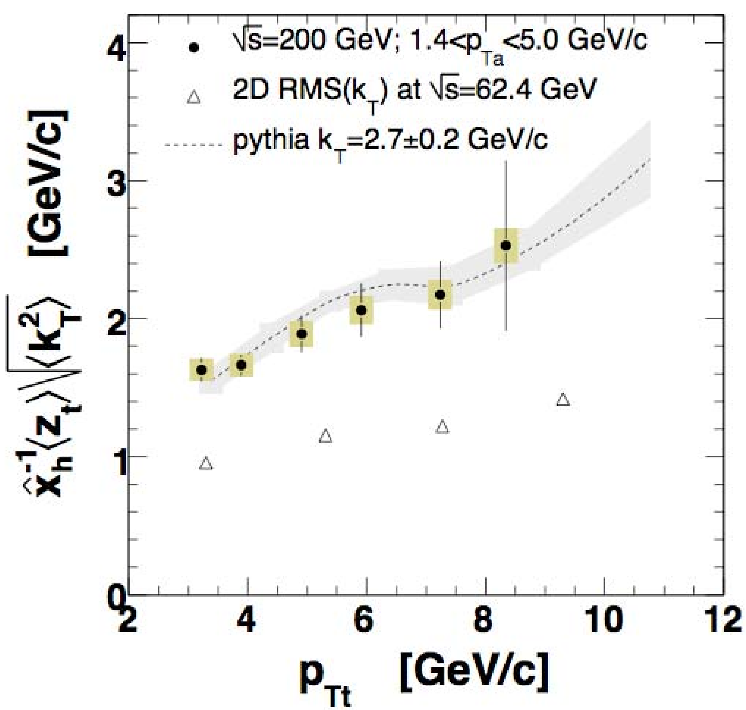
This distribution was adding in PYTHIA code and calculated the azimuthal correlations. The Figure 3 show the experimental data and the simulation. The simulation is in good agreement with the experimental data. The values of $< k_{T1} >$ and $< k_{T2} >$ are 0.558 $\pm$ 0.042 and $< k_{T2} >$ = 0.099 $\pm$ 0.050 respectively. In addition the magnitude of the

“hadronic k_T”

$$\hat{x}_h^{-1}\langle z_t\rangle\sqrt{\langle k_T^2\rangle} = x_h^{-1}\sqrt{\langle p_{out}^2\rangle - \langle j_{Ty}^2\rangle(1+x_h^2)}$$

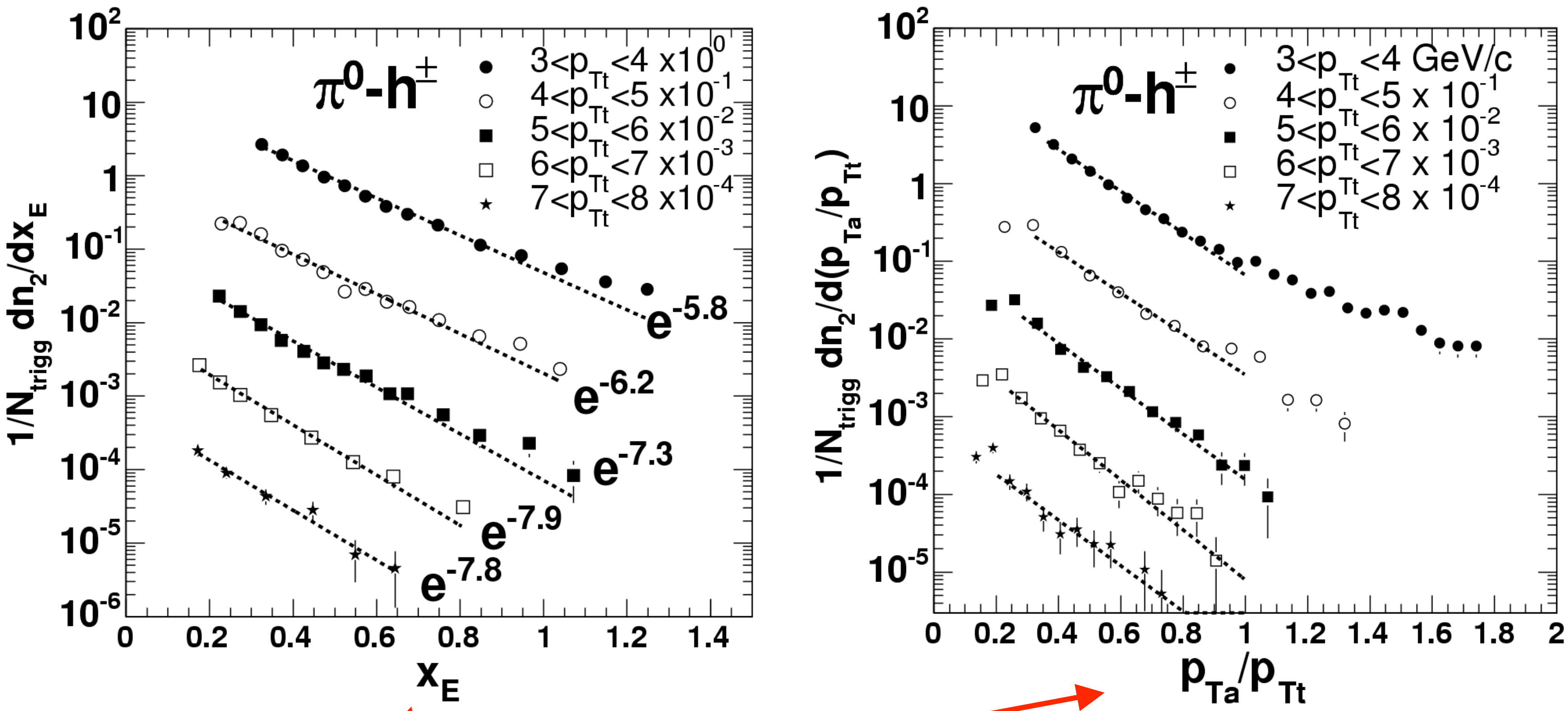
Gray bands - PYTHIA with $\sqrt{\langle k^2_T\rangle}$=2.7±0.2 GeV/c





In order to decompose the partonic variables on the left part of an eqution one has to know the fragmentation function *D(z)*

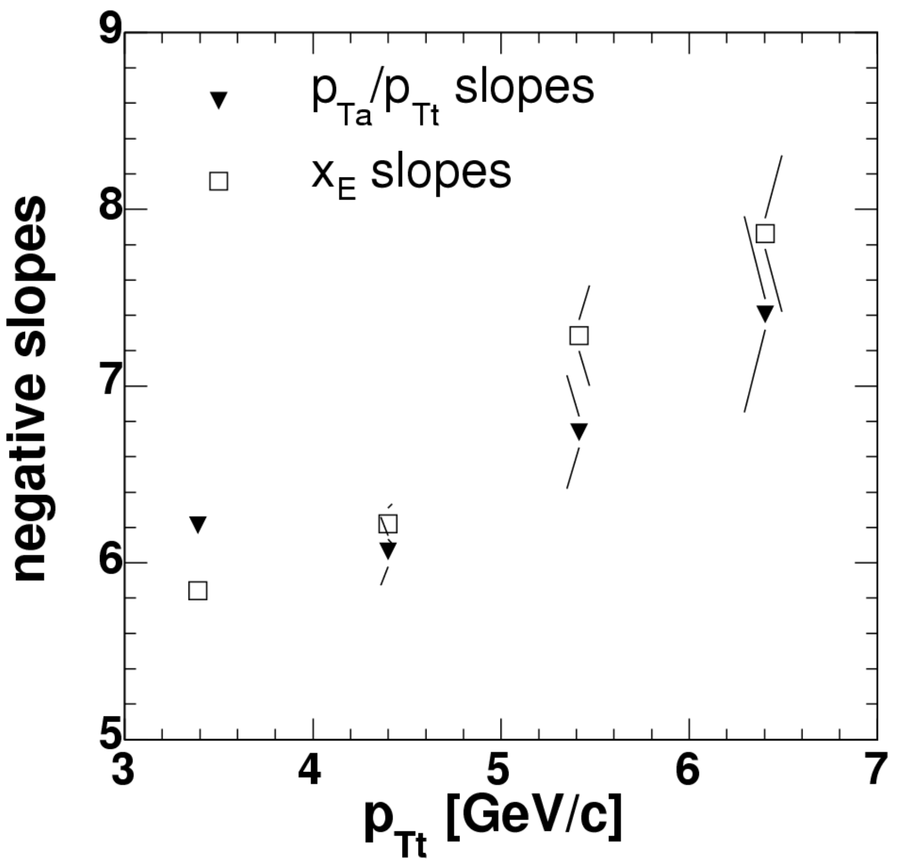
Associated yield in $p+p$ $\sqrt{s}$=200 GeV



$$x_E = -\frac{\vec{p}_{Ta}\cdot\vec{p}_{Tt}}{p_{Tt}^2} = -\frac{p_{Ta}}{p_{Tt}}\cos(\Delta\varphi) = -\frac{z_a\cdot\hat{p}_{Ta}}{z_t\cdot\hat{p}_{Tt}}$$

Both distributions are almost identical. There is no difference between x_E and p_{Ta}/p_{Tt} (see *X.-N. Wang, Phys. Lett.* ***B595****, 165 (2004)*)

Slope variation



Borrowed from Mike

P. Darriulat, ARNPS **30** (1980) 159-210

In contrast to fragmentation function local slope varies with trigger p_{Tt}
There are two reasons:

- trigger bias: fixed momentum of the trigger particle does not fix jet momentum scale
- k_T smearing: imbalance between back-to-back parton momenta

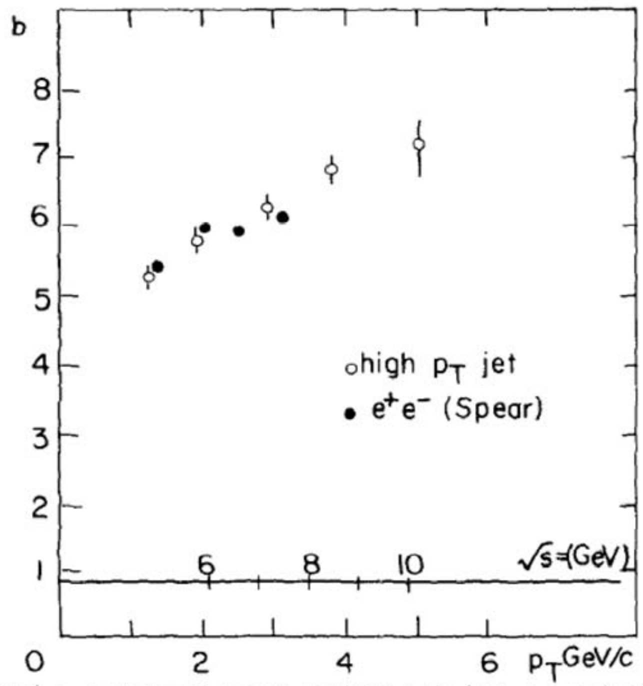
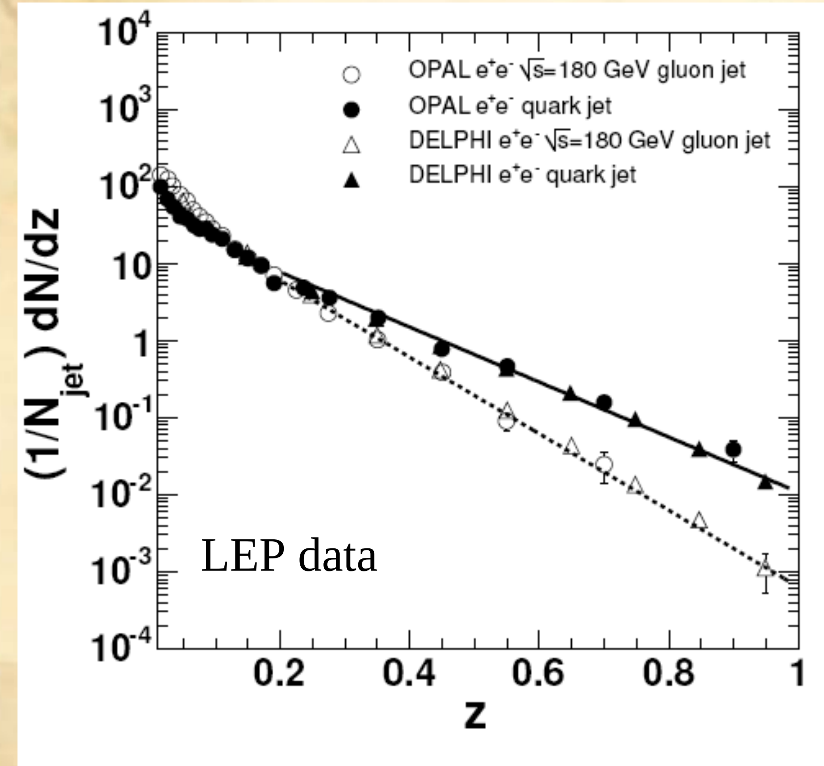
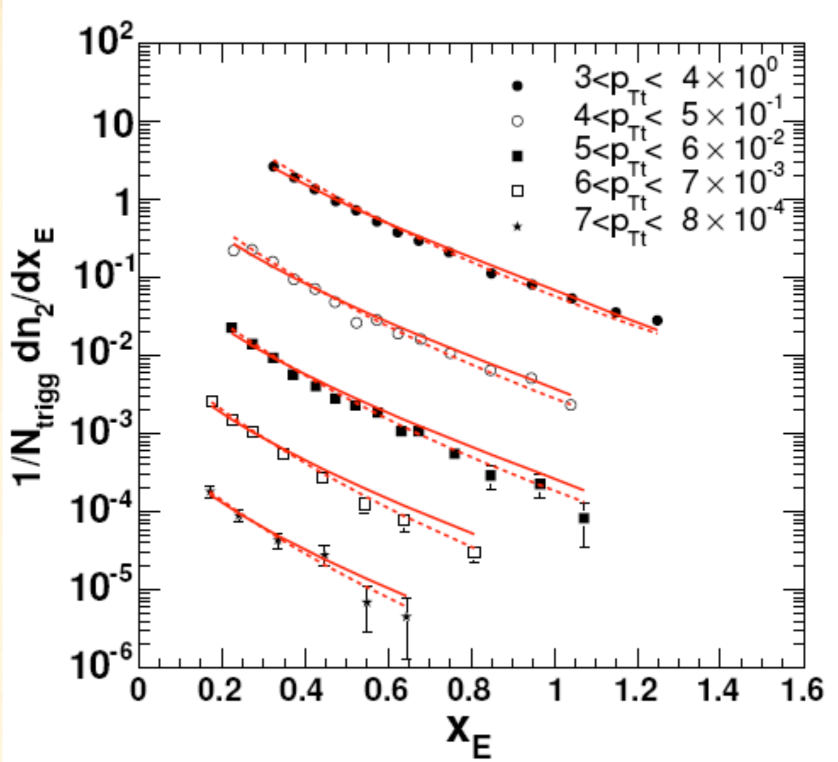


Figure 19 The slopes *b* obtained from exponential fits to the jet fragmentation function in the interval $0.2 < z < 0.8$ in e^+e^- annihilation (*full circles*) and LPTH data of the BS Collaboration (*open circles*).

Trigger associated spectra are insensitive to *D(z)*





MJT Approximation - Incomplete Gamma function when assumed power law for final state PDF and exp for D(z)

$$\frac{d\sigma_\pi}{dp_{T\mathrm{t}}} = \frac{1}{p_{T_t}^{n-1}} \int_{x_{T_t}}^{1} dz_\mathrm{t} z_\mathrm{t}^{n-2} \exp -bz_\mathrm{t} \boxed{\approx \langle m \rangle (n-1) \frac{1}{\hat{x}_\mathrm{h}} \frac{1}{(1+\frac{x_E}{\hat{x}_\mathrm{h}})^n}}$$

Parameterizations of effective D(z) and $\Sigma_Q(\hat{p}_T)$

Associated parton distribution $f_a = kT \otimes f_t$ and the final formula for inclusive cross section:

$$\frac{1}{p_T}\frac{d\sigma_\pi}{dp_T} = \int_{x_T}^{1} \frac{dz}{z^2} \cdot D(z) \cdot \Sigma'_Q\left(\frac{p_T}{z}\right)$$

Inclusive π^0 cross section formula

$$\frac{d^2\sigma_\pi}{dp_{Tt}dp_{Ta}} = \frac{1}{p_{Tt}} \int_{x_{Tt}}^{1} \frac{dz_t}{z_t} \cdot D(z_t) \cdot D\left(\frac{p_{Ta}}{p_{Tt}} z_t\right) \cdot \Sigma'_Q\left(\frac{p_{Tt}}{z_t}\right)$$

Trigger π^0 associated (conditional) cross section formula

$$D(z) = z^\alpha \cdot (1-z)^\beta \cdot (1+z)^\gamma$$

Fragmentation function parameterization

$$\Sigma_Q(\hat{p}_T) \propto \hat{p}_T^{-n}$$

Final state parton spectrum parameterization

Away side distributions

In order to evaluate $\sqrt{\langle k^2_T \rangle}$ and underlying partonic distributions given $CF(p_{Tt},p_{Ta})$ one has to:

1. Compute the trigger-side final PDF - provided D(z).
2. Compute the associated-side final PDF - knowledge of $\sqrt{\langle k^2_T \rangle}$ required.
3. Compute $\langle z_t \rangle$ and $\langle \hat{x}_h \rangle$ and solve (1) for $\sqrt{\langle k^2_T \rangle}$
4. Use this value, go back to 2. And start again.

Key issue: associated parton distribution is calculated according

2D invariant smearing

$$\hat{x}_h^{-1}\langle z_t\rangle\sqrt{\langle k_T^2\rangle} = x_h^{-1}\sqrt{\langle p_{out}^2\rangle - \langle j_{Ty}^2\rangle(1+x_h^2)} \qquad (1)$$

k_T smearing

1D smearing:

$$\Sigma'_Q(\hat{p}_{Tt}) \approx \frac{1}{\sqrt{2\pi\sigma^2_{sm}}} \int_{-\infty}^{\infty} \Sigma_Q(\hat{p}_T - k_T)\cdot \exp\left(-\frac{k_T^2}{2\sigma^2_{sm}}\right) dk_T$$

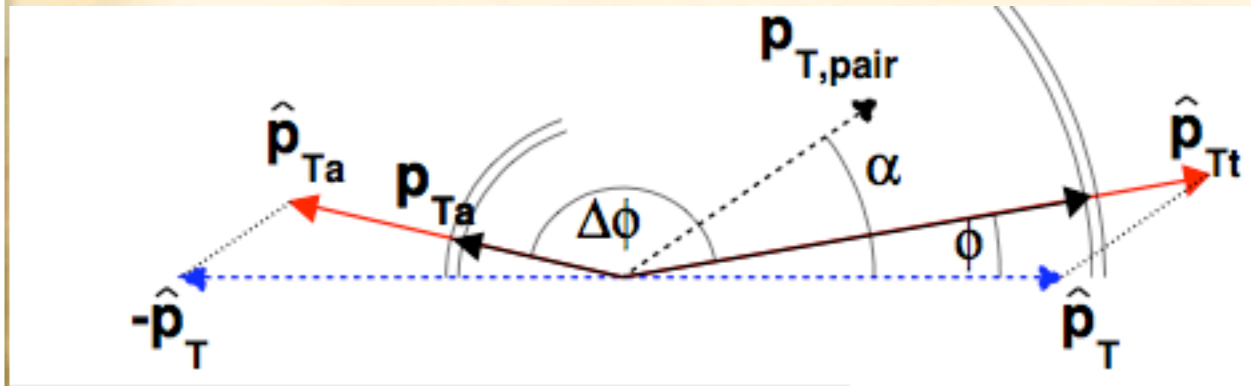
$$\boxed{\sigma^2_{sm} = \langle k^2_{Tx}\rangle / 2}$$

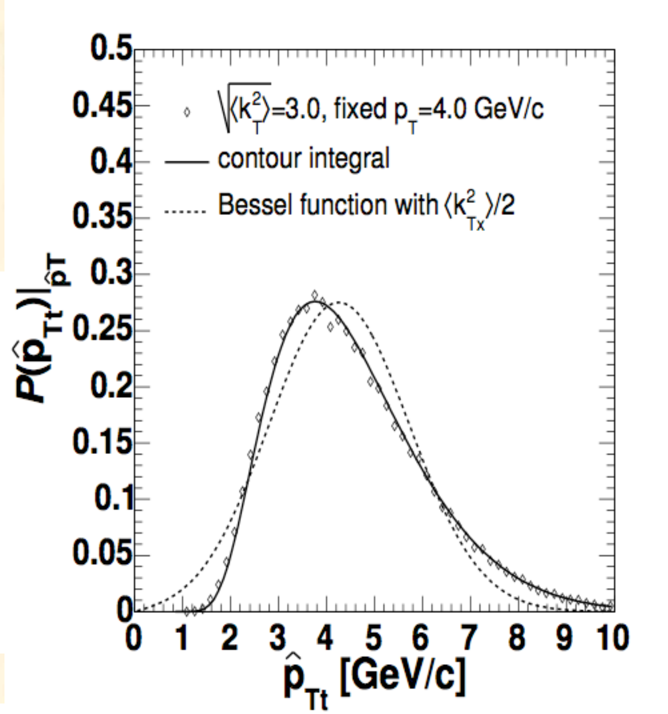
2D smearing:

If we assume the p_{pair} to be a 2D random Gaussian

$p_{T,pair}$ Lorentz boost preserves

$$M^2_{inv} = 4\hat{p}_T^2 = 2\hat{p}_{Tt}\hat{p}_{Ta} - 2\vec{\hat{p}}_{Tt}\vec{\hat{p}}_{Ta}$$





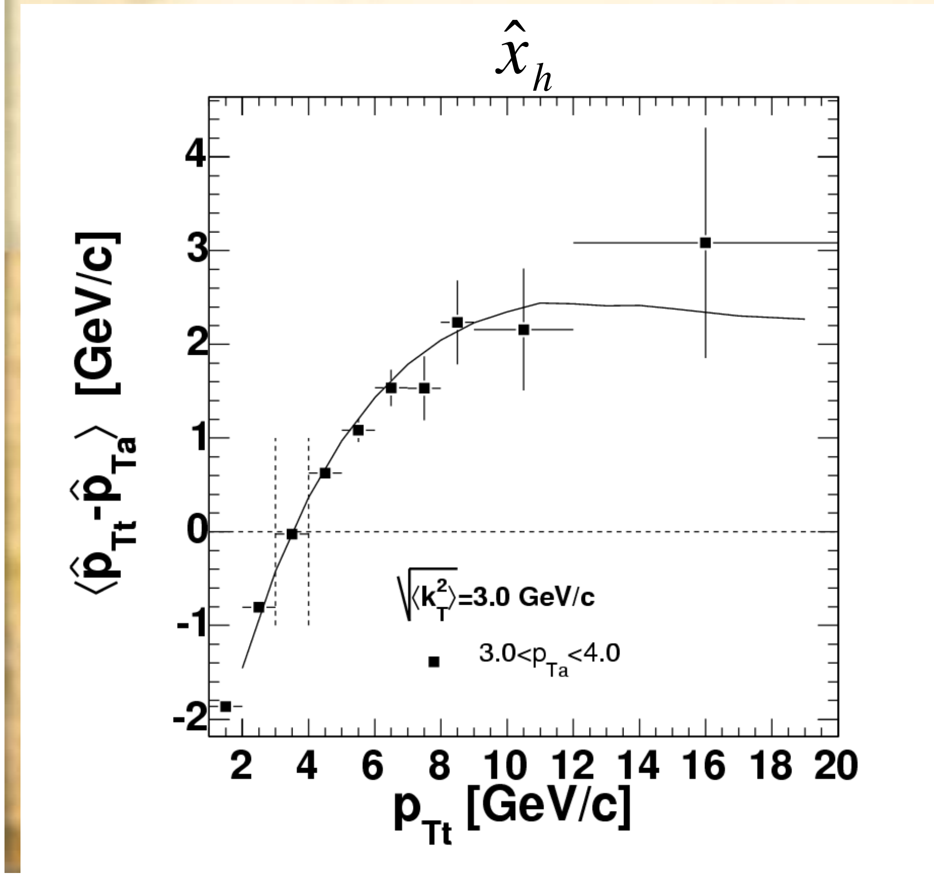
$$\left.\frac{d\sigma}{d\hat{p}_{Tt}\,d\alpha\,d\hat{p}_T}\right|_{p_{Tt},p_{Ta}} = \hat{p}_{Tt}\cdot\Sigma_q(\hat{p}_T)\cdot\hat{p}_n\cdot G(\hat{p}_n(\vec{r}_t))\cdot D^q_\pi\left(\frac{p_{Tt}}{\hat{p}_{Tt}}\right)\frac{p_T}{\hat{p}^2_{Tt}}\cdot D^q_\pi\left(\frac{p_{Ta}}{\hat{p}_{Ta}(\vec{r}_t)}\right)\frac{p_{Ta}}{\hat{p}^2_{Ta}(\vec{r}_t)}$$

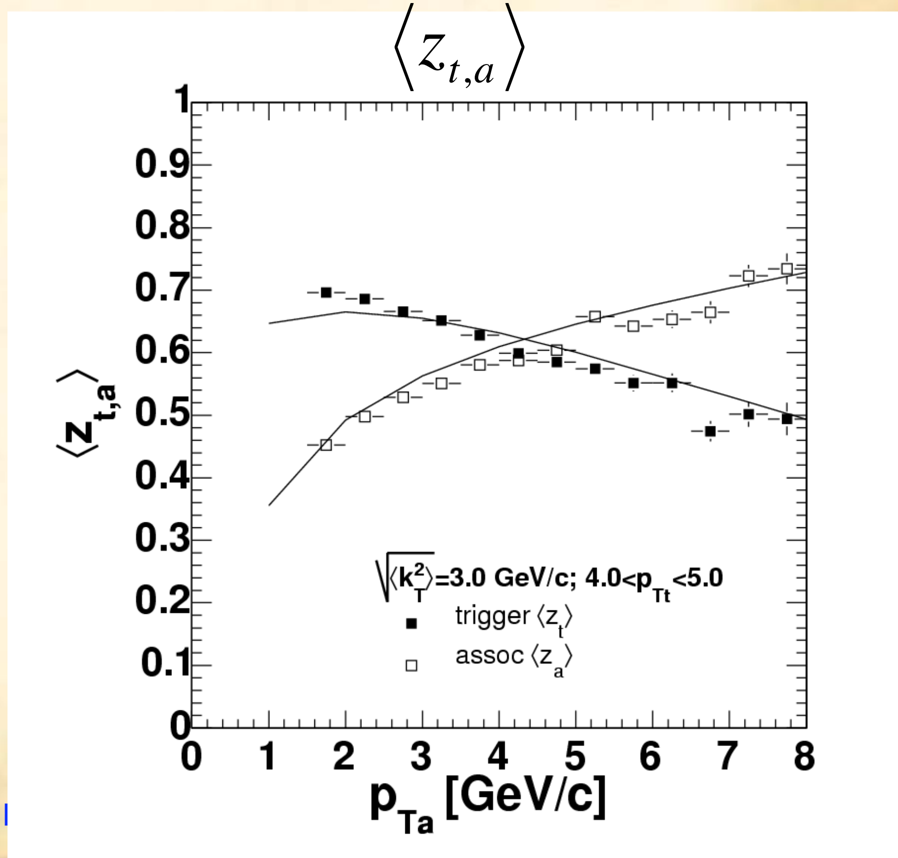
Comparison with PYTHIA

W integrated

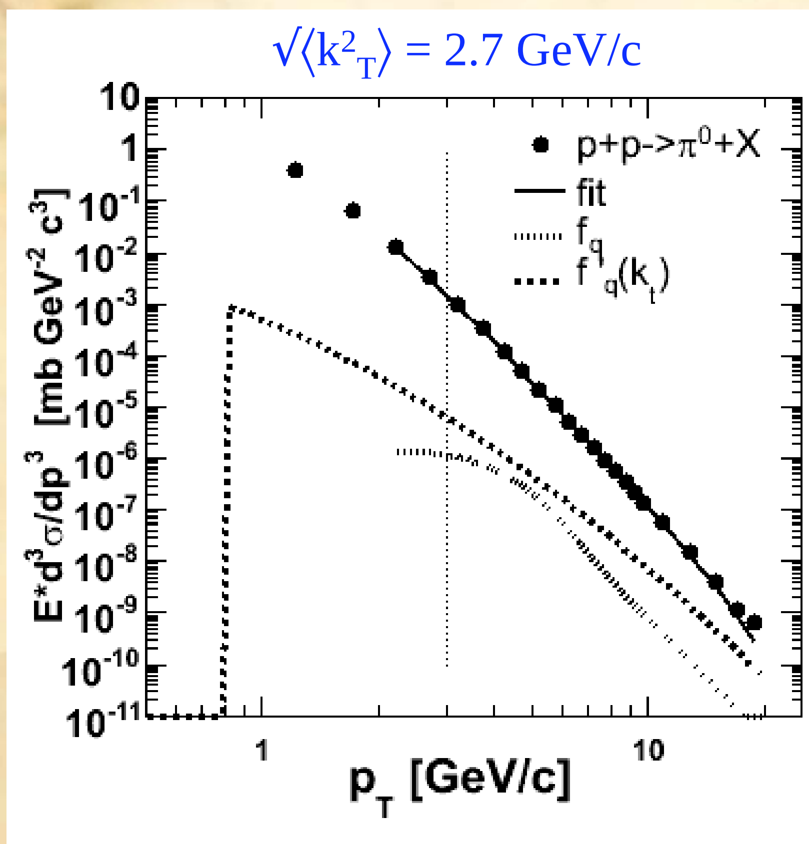
$$\frac{d\sigma}{d\hat{p}_{T\mathrm{t}}\, d\alpha\, d\hat{p}_T}\bigg|_{p_{T\mathrm{t}},p_{T\mathrm{a}}} = \hat{p}_{T\mathrm{t}} \cdot \Sigma_q(\hat{p}_T) \cdot \hat{p}_{\mathrm{n}} \cdot G(\hat{p}_{\mathrm{n}}(\vec{r}_t)) \cdot D_\pi^q\left(\frac{p_{T\mathrm{t}}}{\hat{p}_{T\mathrm{t}}}\right)\frac{p_T}{\hat{p}_{T\mathrm{t}}^2} \cdot D_\pi^q\left(\frac{p_{T\mathrm{a}}}{\hat{p}_{T\mathrm{a}}(\vec{r}_t)}\right)\frac{p_{T\mathrm{a}}}{\hat{p}_{T\mathrm{a}}^2(\vec{r}_t)}$$

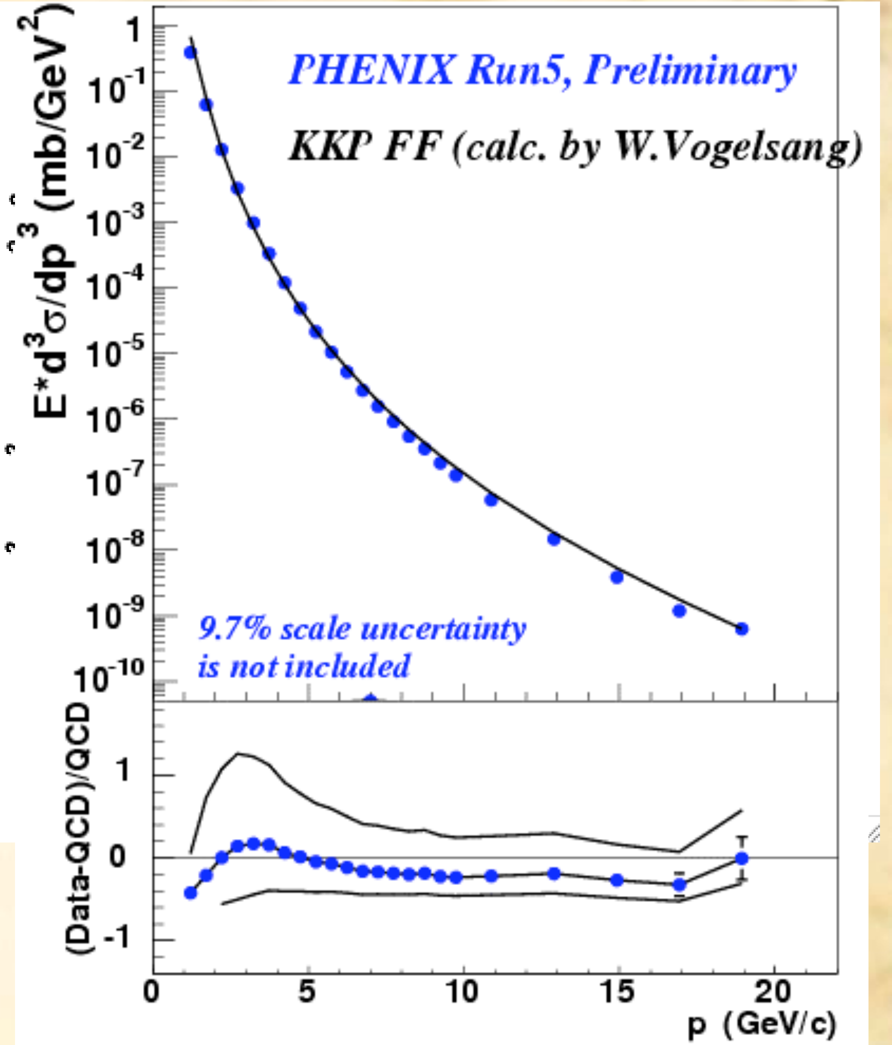
aver angle α, calculated the momentum imbalance and mean trigger and associated $z_t\, z_a$, compared to pythia.





Bonus for Peter L.



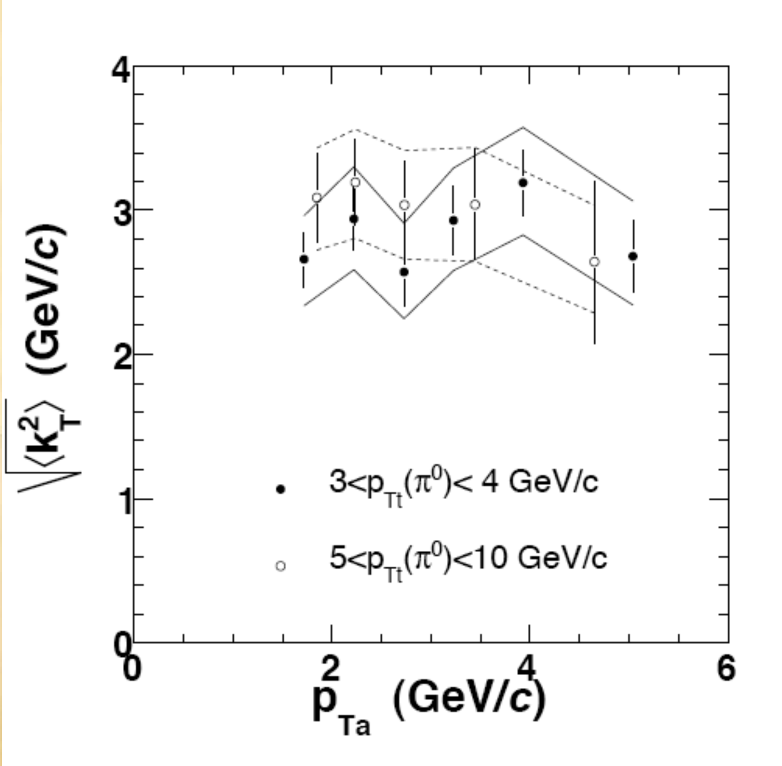


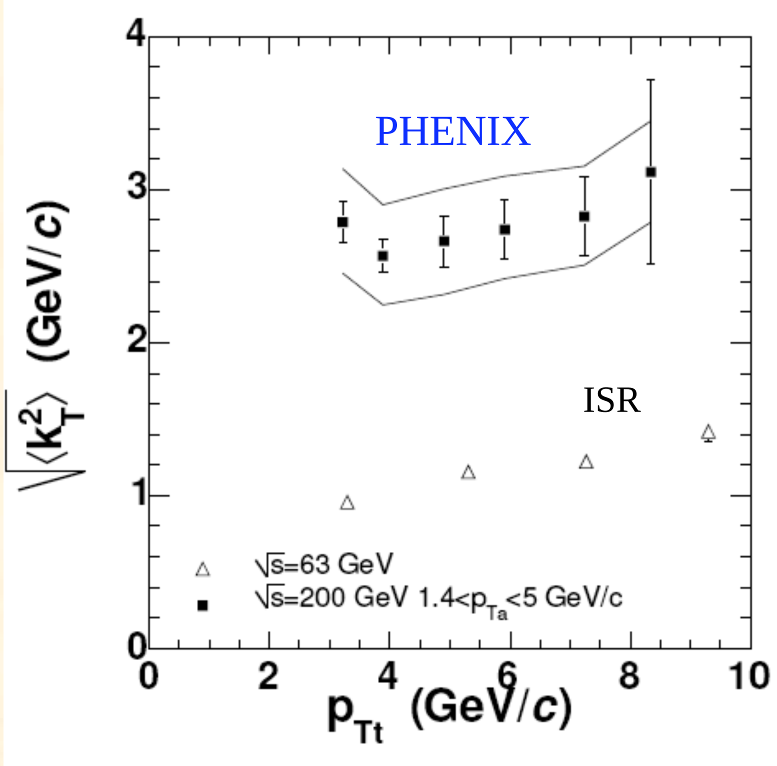
I found Peter's critique always useful. If you drop the last point and move NLO accordingly down you find amazing agreement with kT=2.7 GeV/c !!

Results RMS k_T in p+p @ 200 GeV

We gave up an effort to extract fragmentation function from di-hadron data, direct photon analysis under way - stay tuned ….

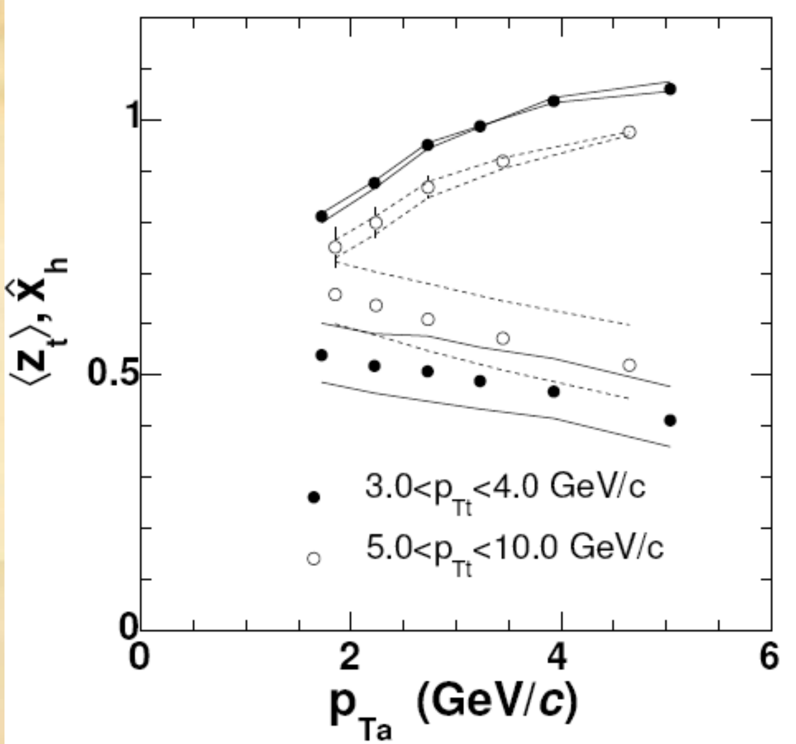
For D(z) the LEP date were used.

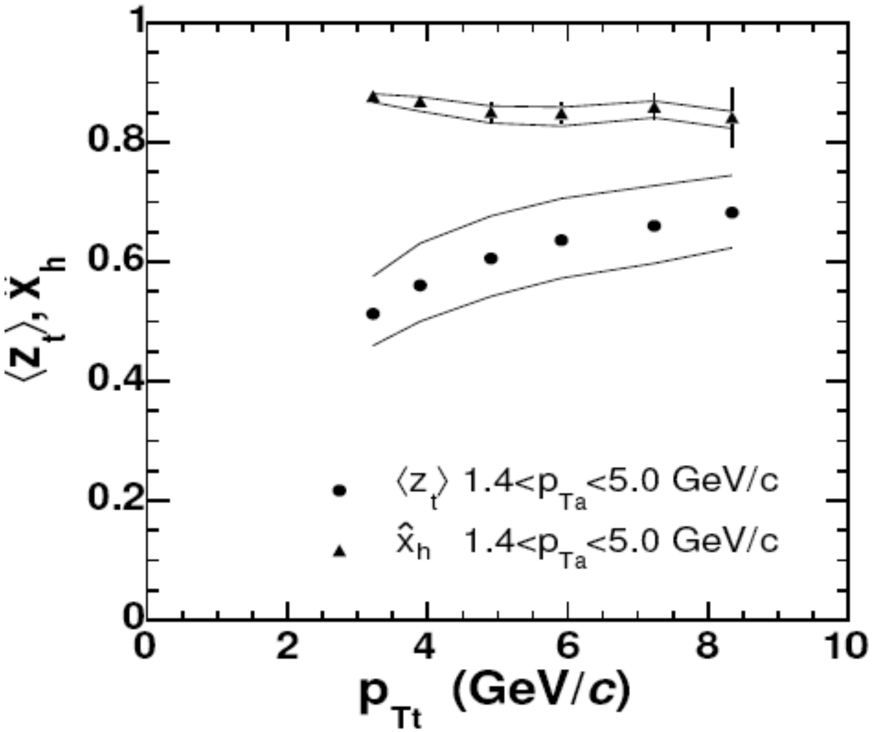




Main contribution to the systematic errors comes from unknown ratio gluon/quark jet => D(z) slope.

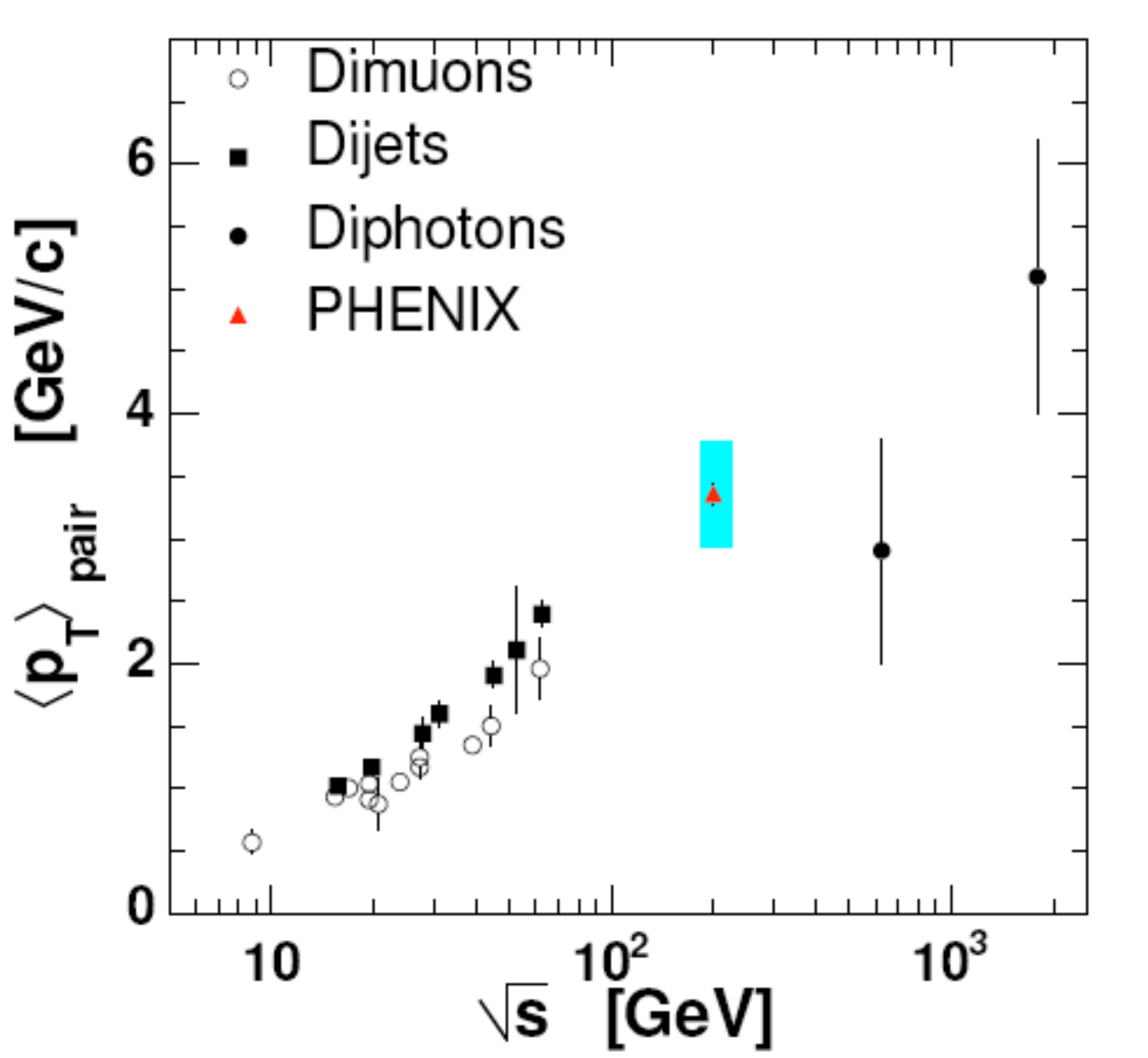
Mean z and jet momenta imbalance





Main contribution to the systematic errors comes from unknown ratio gluon/quark jet => D(z) slope.

p_{Tt} integrated $\sqrt{\langle k^2_T \rangle}$



L. Apanasevich *et al.*, Phys. Rev. **D59**, 074007 (1999).

summary

We may learn everything what we want from di-hadron correlations except the Fragmentation function. However, there are facts not quite commonly understood:

- Away-side peak variance does not measure RMS of p_{out} .
- Fixed trigger momentum doesn’t fix the jet momentum. The <z> variation propagates to the away side jet.
- k_T smearing – strong bias towards smaller parton momenta and k_T pointing towards you.
- Gaussian 1D approximation for the k_T smearing may be too rough even at relatively high p_T region around 10 GeV/c.
- associated distribution in p_{Tassoc}, p_{Tassoc}/p_{Ttrigg} or in x_E are convolutions of parton distribution function, product of two fragmentation function and k_T and their sensitivity to the shape of the fragmentation function is suppressed by factor of $2/\sqrt{s}$.

Exctracted $\sqrt{\langle k^2_T \rangle}$ seems to follow general trend with $\sqrt{s}$. The p_{Tt} dependence seems to be shallower than what has been observed at lower energies - this could be because of $\langle z \rangle$ variations were neglected.